Predictive Torque and Flux Control of an Induction Machine fed by an Indirect Matrix Converter with Reactive Power Minimization

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***Abstract-* A predictive torque and flux control method for an induction machine fed by an indirect matrix converter is presented in this paper. The control scheme selects the switching state that minimizes the error in the torque and flux predictions according to their reference values and, at the same time, the control scheme is enhanced by including a reactive power minimization strategy with the goal to have unity power factor in the input side of the converter. The control objectives are accomplished by using a prediction horizon of one sample time and a very intuitive control law. The proposed control scheme is validated trough simulation results where is shown that the predictive approach can be implemented simply with a good tracking of the torque and flux to their respective references and input currents with unity power factor.**

I. Introduction

Nowadays, ac/ac converter systems with either a voltage or current dc-link have been widely studied and are mainly used in the industry. Due to the dc-link storage element (capacitor or inductor), there is the advantage that both converter stages (rectifier and inverter) are to a large extend decoupled for control purposes, but the dc-link energy storage component has a relative large physical size and thus reduce the system lifetime. Moreover, there are also ac/ac converter systems without any intermediate dc-link storage element, where different topologies have been reported in the literature, which are classified into three main groups: the cycloconverter in a wide power variety, the direct matrix converter (DMC) and the indirect matrix converter (IMC), both in low power range [1]. The cycloconverter is very common in high power applications such as cement kilns and ball mills in mineral processing, but has a major limitation in terms of output frequency with respect to the input, because the presence of a high harmonic content due the commutations, which can not be filtered by the load inductance. On the other hand, the DMC is based on bi-directional switches and carry out voltage and current conversion in only one stage, being a preferred choice when the size and the need to remove the dc-link stage are significant issues. But the biggest drawback of this technology is the great control complexity. IMC offers the same performance that the DMC [2]-[4], such as four-quadrant operation, unit power factor, sinusoidal waveforms with variable frequency and amplitude during motoring and regeneration operation, however, the control in this converter is simpler and less complex compared to the DMC, allowing also the system to commutate securely [5][6] without particular sensing devices as required for the DMC [7]. A further improvement compared to the DMC is that no additional over-voltage protection circuit is required. Different works have been reported in the literature [8]-[11] that implements the torque control in electrical machines considering back-to-back and matrix converters with the use of complex Pulse Width Modulation (PWM) schemes to achieve the goal of unity power factor and sinusoidal output current. However, since power converters have a discrete nature, the application of predictive control constitutes a promising and better suited approach as compared to standard schemes that use mean values of the variables. Furthermore, predictive control utilizes the system model to predict the future behavior of variables to a predefined time horizon and selects the optimal action based on the minimization of a cost function [12]-[14]. This structure is characterized because its concepts are very intuitive and easy to understand, it can be applied to a wide variety of systems, may involve multiple systems, dead time compensation, and non-linear constraints, resulting in an easy controller to be implemented, being open to modifications and extensions for specific applications as reviewed in [15]-[21]. This paper considers the advantages of predictive control and the indirect matrix converter, to control in an easy, an intuitive and a new manner, the torque and flux variables of an induction machine fed by the converter while ensuring a unitary power factor at the input system of the converter. The predictive approach is based on the fact that only a fixed numbers of feasible switching states can be generated by a static power converter and that the models of the system can be used to determine the behavior of the variables for each commutation state. The work is presented as follows. Section II presents the fundaments of the indirect matrix converter where is described its mathematical model

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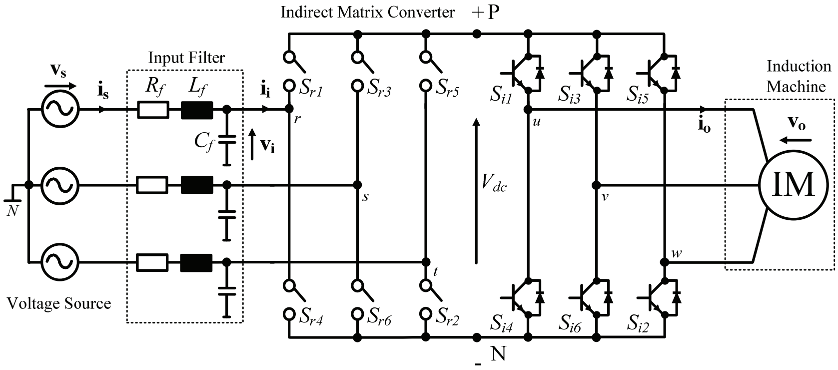

Fig. 1. Indirect matrix converter topology.

and the relation between the input and output variables. Section III describes the mathematical model of the induction machine, section IV depicts the control strategy proposed, validated with simulation results in Section V, and finally conclusions are expressed in Section VI.

II. Fundaments of the Indirect Matrix Converter

The converter topology is shown in Fig. 1, and it consists of a rectifier connected to the inverter through a dc-link without energy storage element. The converter synthesizes a positive voltage in the dc-link by selecting a switching state in the rectifier that connects one phase to the point P and the other phase to the point N. In addition, the rectifier includes an LC filter in the input side which is needed to prevent over voltages and to provide filtering of the high frequency components of the input currents produced by the commutations and the inductive nature of the load. The dc-link voltage v_{dc} is synthesized by the input voltages $\mathbf{v_i} = [v_i^r\ v_i^s\ v_i^t]^T$ and the switching states as follow,

$$v_{dc} = \begin{bmatrix} S_{r1} - S_{r4} & S_{r3} - S_{r6} & S_{r5} - S_{r2} \end{bmatrix} \mathbf{v_i}, \tag{1}$$

where $S_{r1} \ldots S_{r6}$ are the switching states of the rectifier stage. In addition, the input current $\mathbf{i_i} = [i_i^r\ i_i^s\ i_i^t]^T$, is doing by the switching state and the dc-link current i_{dc}, as:

$$\mathbf{i_i} = \begin{bmatrix} S_{r1} - S_{r4} \\ S_{r3} - S_{r6} \\ S_{r5} - S_{r2} \end{bmatrix} i_{dc}, \tag{2}$$

The dc-link current i_{dc}, is determined by the switching states of the inverter stage $S_{i1} \ldots S_{i6}$, and the output current $\mathbf{i_o} = [i_o^u\ i_o^v\ i_o^w]^T$ as follow,

$$i_{dc} = \begin{bmatrix} S_{i1} & S_{i3} & S_{i5} \end{bmatrix} \mathbf{i_o} \tag{3}$$

and the output voltage $\mathbf{v_o} = [v_o^u\ v_o^v\ v_o^w]^T$ is determined by the switching states of the inverter stage and the dc-link voltage v_{dc} as,

$$\mathbf{v_o} = \begin{bmatrix} S_{i1} - S_{i4} \\ S_{i3} - S_{i6} \\ S_{i5} - S_{i2} \end{bmatrix} v_{dc}. \tag{4}$$

The line side of the rectifier consists of a second order system described by:

$$L_f \dot{\mathbf{i}}_\mathbf{s} = \mathbf{v_s} - \mathbf{v_i} - R_f \mathbf{i_s}, \tag{5}$$

$$C_f \dot{\mathbf{v}}_\mathbf{i} = \mathbf{i_s} - \mathbf{i_e}, \tag{6}$$

where L_f involves the mains and filter inductances, and R_f the mains and filter damping resistances. The rectifier stage can produce only positive dc-link voltage in each sampling time (3 of 9 possible switching states accomplish this request), so the number of valid switching states is 24. It should be noted that the IMC topology includes as many switches as the DMC, but the former features an extra freedom degree that alleviates the complexity of the commutation sequence [5][6].

III. Model of the Induction Machine

To obtain the model of the system, it will be assumed that the three phase quantities of the converter are symmetrical and therefore, can be represented by a two-dimensional space vector. For example, the phase components x_u, x_v, and x_w will be described by the complex space vector:

$$\mathbf{x} = x_\alpha + jx_\beta, \tag{7}$$

which is defined as:

$$\left.\begin{aligned} x_\alpha &= \frac{1}{3}\left(2x_u - x_v - x_w\right) \\ x_\beta &= \frac{1}{\sqrt{3}}\left(x_v - x_w\right) \end{aligned}\right\}, \tag{8}$$

This space vector is referred to a stationary reference frame that will be considered as an $\alpha\beta$-reference frame. The model of the induction machine referred to stator is obtained as described in [17]. Hence, the induction machine model in space vector representation is given by (9) and (10), where the stator and rotor voltage equations in fixed coordinates are presented as:

$$\mathbf{v_o} = R_s \mathbf{i_o} + L_s \dot{\boldsymbol{\psi}}_\mathbf{s} \tag{9}$$

$$\mathbf{v_r} = R_r \mathbf{i_r} + L_r \dot{\boldsymbol{\psi}}_\mathbf{r} - jp\omega \boldsymbol{\psi}_\mathbf{s} \tag{10}$$

where R_s, R_r and ω correspond to the stator resistance, rotor resistance, and rotor angular frequency, p as the ac machine number of pole pairs, in that order. The stator and rotor fluxes are related with their respective currents trough the equations,

$$\boldsymbol{\psi}_\mathbf{s} = L_s \mathbf{i_o} + L_m \mathbf{i_r} \quad \text{and} \quad \boldsymbol{\psi}_\mathbf{r} = L_r \mathbf{i_r} + L_m \mathbf{i_o} \tag{11}$$

where L_s, L_r, and L_m correspond to the self and mutual inductances respectively. Finally, the electric torque can be expressed in current and flux terms such as,

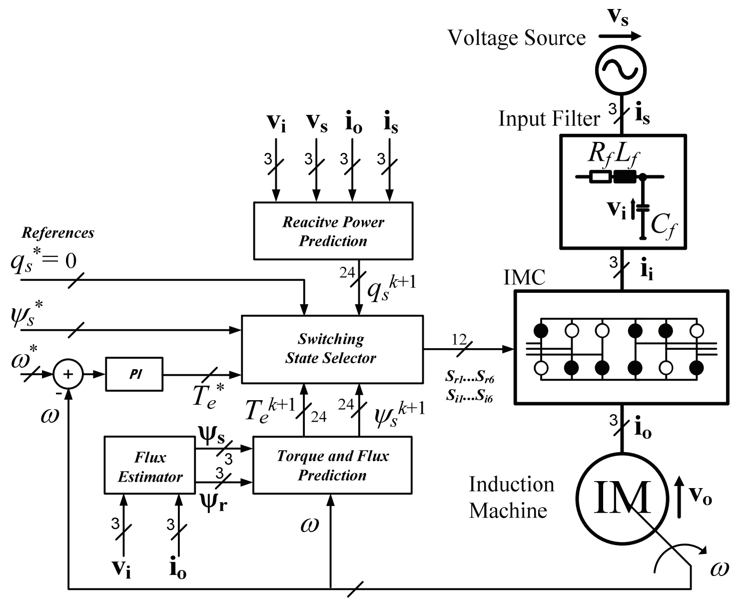

Fig. 2. Proposed control strategy scheme.

$$T_e = \frac{2}{3} p(\boldsymbol{\psi}_\mathbf{s} \times \mathbf{i_o}) \,. \tag{12}$$

IV. Proposed Scheme: Predictive Torque and Flux Control of an Induction Machine

A. Proposed Control Strategy

Predictive control considers the advantage of the discrete nature of power converters, which have a finite number of valid commutation states because they are based on discrete switches, which have only two states: ON and OFF. The proposed predictive control scheme is represented in Fig. 2. The approach pursues the selection of the switching state of the converter that leads the torque and flux closest their respective references at the end of the sampling instant. At the same time, the line side of the rectifier must deliver active power and finally the dc-link voltage must be always positive. These before mentioned conditions are fulfilled by the predictive controller in five steps as follow:

1. The input voltages $\mathbf{v_s}^k$, $\mathbf{v_i}^k$, input currents $\mathbf{i_s}^k$, stator currents $\mathbf{i_o}^k$ and speed ω^k of the induction machine are measured.
2. The speed ω^{*k}, flux ψ_s^{*k} and reactive power q_s^{*k} references correspond at given values, although the torque T_e^{*k} reference is established by a PI linear controller which have as input the error between the reference and measured speed values of the induction machine as explained in section IV.B.
3. The stator and rotor flux estimations, are obtained by a flux estimator described in section IV.C.
4. The model of the system is used to predict in the next sampling time the value of the torque T_e^{k+1}, flux ψ_e^{k+1} and reactive power q_s^{k+1}, for each of the valid switching states according exposed in section IV.C.
5. As a final point, the predicted values are used to evaluate a cost function which deals with the torque, flux and the input power factor errors as indicated in section IV.D. After that, the valid switching state that produces the minimum value of the cost function is selected for the next sampling period. As mentioned before, the method is represented in Fig. 2, where it is possible to appreciate that the control algorithm is easy to understand and implement which demonstrates that the use of predictive control can avoid the use of complex modulation techniques.

B. Steps 1-2 Measurements, References and Speed Control

As mentioned before, to implement the control algorithm it is necessary to obtain the measurements and references values of the interesting variables. The speed is controlled using an external controller which generates the torque reference used to make the gating patterns as mentioned before. The controller is a PI because the integral part is required in order to achieve zero steady state error, due to the fact that the predictive torque control fast dynamic can be represented just as a unity gain between the reference and the controlled variables.

C. Steps 3-4 Flux Estimations and Calculation of Predicted Values

With the assumption that it is possible to define a first order approximation for the derivatives due to the first order nature of the state equations that describes the induction machine model (9)-(12) as,

$$\dot{x} = \frac{x^{k+1} - x^k}{T_s} \tag{13}$$

where T_s is the sampling period, so, the stator and rotor fluxes can be estimated from (9)-(10) resulting in,

$$\boldsymbol{\psi}_\mathbf{s}^k = \boldsymbol{\psi}_\mathbf{s}^{k-1} + \mathbf{v_o}^k T_s - R_s \mathbf{i_o}^k T_s \tag{14}$$

$$\boldsymbol{\psi}_\mathbf{r}^k = \frac{L_r}{L_m} \boldsymbol{\psi}_\mathbf{s}^{k-1} + \left(L_m - \frac{L_s L_r}{L_m} \right) \mathbf{i_o}^k \tag{15}$$

Thus, according to [18] it is possible to obtain a stator flux prediction as,

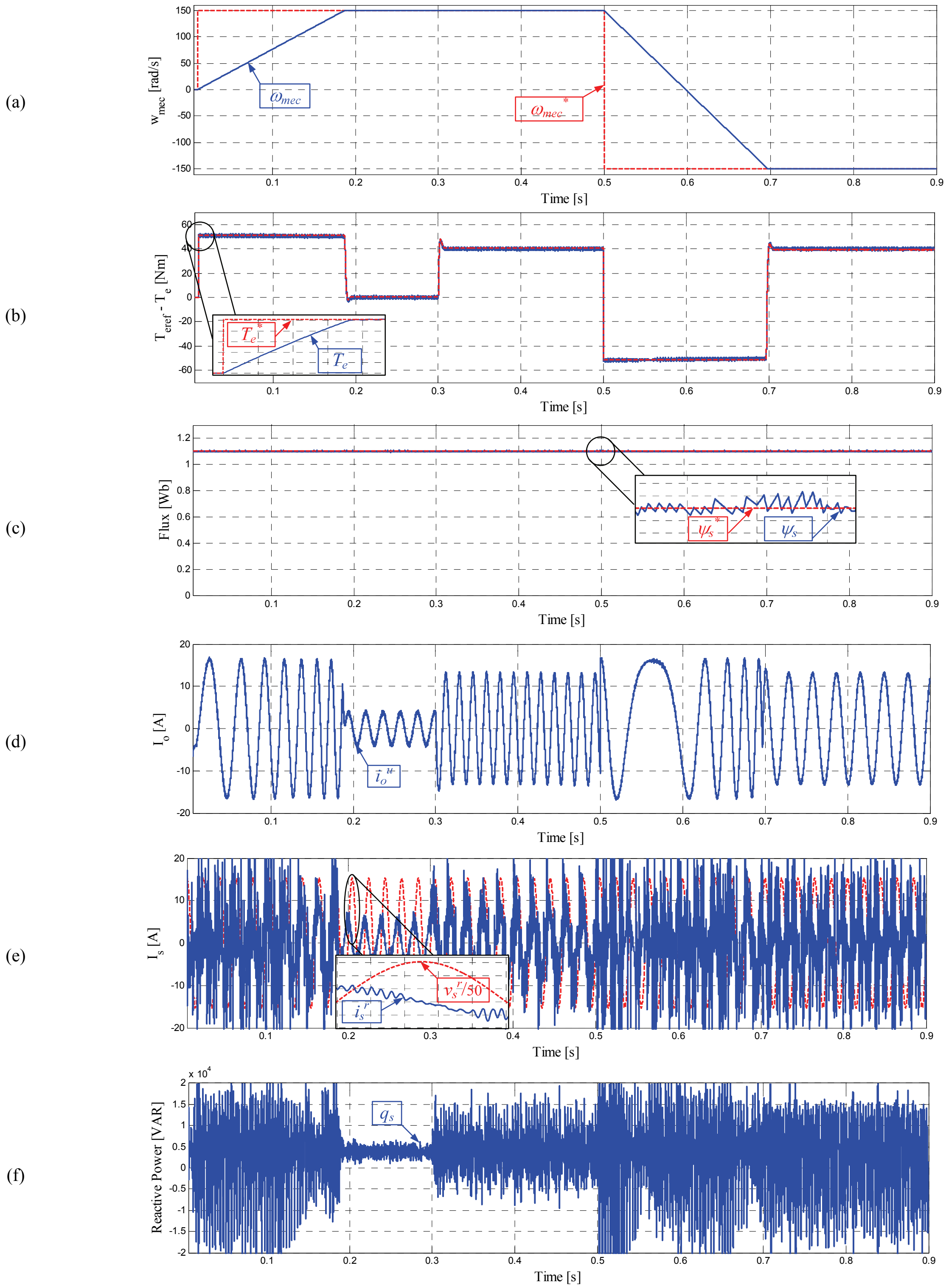

Fig. 3. Simulation results without reactive power minimization:
(a) ω_{mec}: mechanic speed, (b) T_e: electric torque and T_e^*: reference; (c) ψ_s: stator flux and ψ_s^*: reference;
(d) i_o^u: load current; (e) i_s^r: source current and $v_s^r/50$: source voltage; (f) q_s: source reactive power.

$$\boldsymbol{\psi}_\mathbf{s}^{k+1} = \boldsymbol{\psi}_\mathbf{s}^{k} + \mathbf{v}_\mathbf{o}^{k+1} T_s - R_s \mathbf{i}_\mathbf{o}^{k+1} T_s, \qquad (16)$$

where $\mathbf{v}_\mathbf{o}^{k+1}$ is given by (4) and the stator current prediction equation [18] is,

$$\mathbf{i}_\mathbf{o}^{k+1} = \left(1 - \frac{r_\sigma T_s}{\sigma L_s}\right) \mathbf{i}_\mathbf{o}^{k} T_s + \frac{T_s}{\sigma L_s} \cdot \left(\mathbf{v}_\mathbf{o}^{k+1} + \left(\tau_r k_r - j k_r \omega\right)\right) \boldsymbol{\psi}_\mathbf{r}^{k} \qquad (17)$$

where,

$$r_\sigma = R_s + R_r k_r^2,\ \sigma = 1 - k_r k_s,\ \tau_r = L_r / R_r,\ k_r = L_m / L_r,$$
$$k_s = L_m / L_s \qquad (18)$$

The predicted electrical torque, for the next sample time, is deduced from (12) and (16)-(17) as,

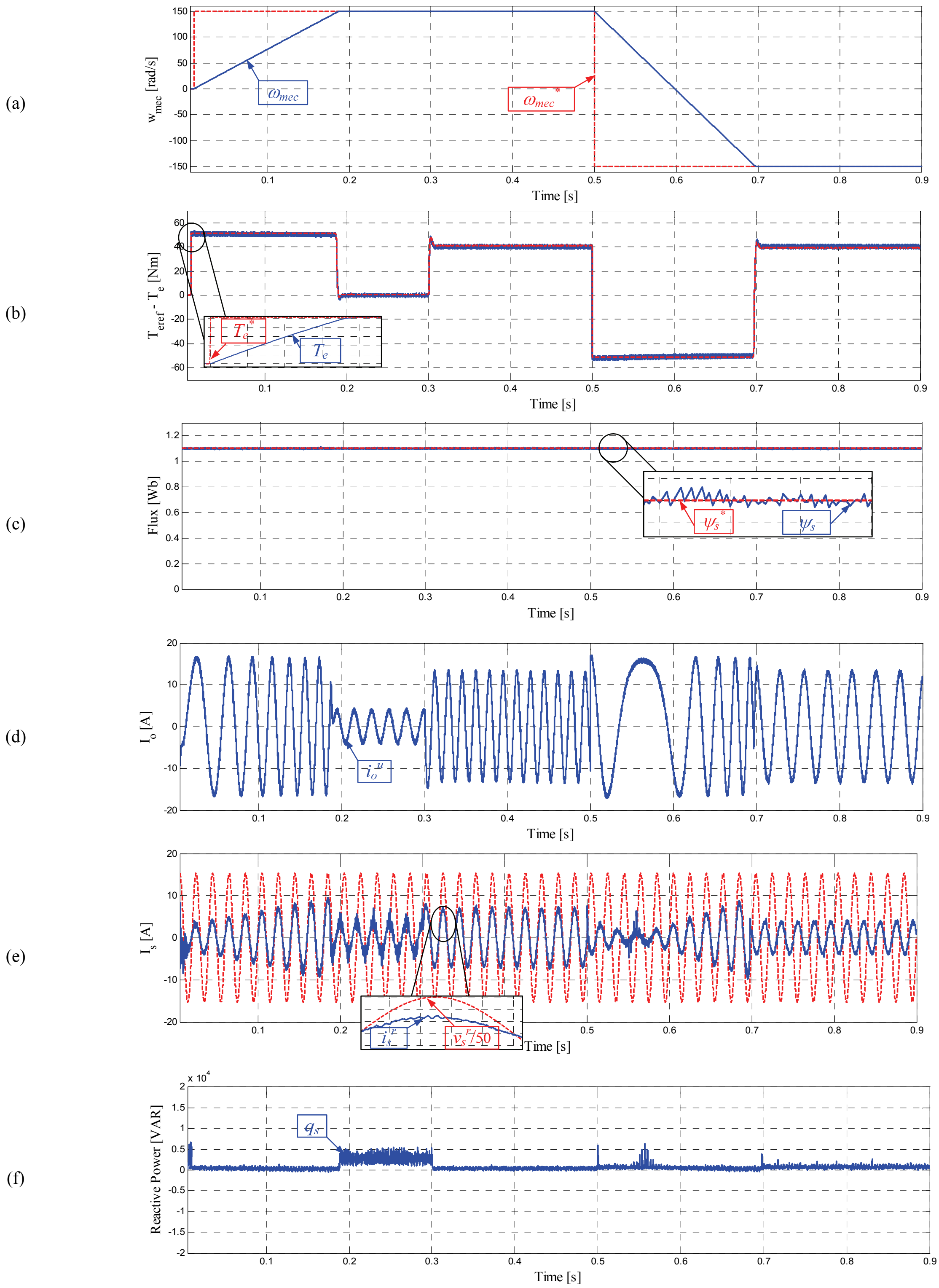

Fig. 4. Simulation results with reactive power minimization:
(a) ω_{mec}: mechanic speed, (b) T_e: electric torque and T_e^*: reference; (c) ψ_s: stator flux and ψ_s^*: reference;
(d) i_o^u: load current; (e) i_s^r: source current and $v_s^r/50$: source voltage; (f) q_s: source reactive power.

$$T_e^{k+1} = \frac{2}{3} p \left(\boldsymbol{\psi}_s^{k+1} \times \mathbf{i}_o^{k+1} \right) \tag{19}$$

The prediction of the input current and capacitor voltages are computed from a first order differential equation, as is described follows,

$$\mathbf{i}_s^{k+1} = \phi_{21}\mathbf{v}_i^k + \phi_{22}\mathbf{i}_s^k + \gamma_{21}\mathbf{v}_s^k + \gamma_{22}\mathbf{i}_i^k \,, \tag{20}$$

$$\mathbf{v}_i^{k+1} = \phi_{11}\mathbf{v}_i^k + \phi_{12}\mathbf{i}_s^k + \gamma_{11}\mathbf{v}_s^k + \gamma_{12}\mathbf{i}_i^k \,. \tag{21}$$

The real coefficients ϕ_{ij} and γ_{ij} are defined so that the obtained values for the predicted currents correspond to those of the continuous time system after one sampling time, as exposed in [23].

D. Step 5. Cost Function (Switching State Selector)

Different control criteria will be expressed in different quality function but in this work, the absolute error is considered for computational simplicity. So, the error between the predicted electrical torque and its reference can be expressed as follow,

$$\Delta T_e^{k+1} = \left| T_e^* - T_e^{k+1} \right|, \tag{22}$$

where T_e^{k+1} denotes the electrical torque for k+1 sample time, and T_e^* its respective reference. Also, the error between the predicted values of the stator flux and its reference can be represented as,

$$\Delta \psi_s^{k+1} = \left| \psi_s^* - \psi_s^{k+1} \right|, \tag{23}$$

furthermore, the error between the reference and the predicted value of the instantaneous reactive power is given by,

$$\Delta q_s^{k+1} = \left| 0 - (v_{s\alpha}^{k+1} i_{s\beta}^{k+1} - v_{s\beta}^{k+1} i_{s\alpha}^{k+1}) \right|. \tag{24}$$

Finally, the equations (22)-(24) are combined into a single so-called quality function:

$$g^{k+1} = A\Delta T_e^{k+1} + B\Delta \psi_s^{k+1} + C\Delta q_{in}^{k+1}. \tag{25}$$

where A, B, and C are the weight coefficients which denotes the priority in the control. The proposed predictive scheme operates as follows: at each sampling time, all possible switching states are used to calculate the eq. 25. The switching state that produces the minimum value of g is selected to be applied for the next one sampling period [16]-[23].

V. Simulation Results

The predictive strategy is simulated in order to validate the proposed control scheme. The simulation parameters are indicated in Table I and the sampling period of the control algorithm was set in T_s = 10μs. Two cases are considered; the first one includes the control of torque and flux, but does not includes the minimization of the reactive power (C = 0) and the second one minimizes at the same time, the torque and flux of the induction machine and reactive power in the input system. Both test considers the starting of the induction machine at t = 0.05s without a load torque, applying a speed reference change from 0 to 1430 RPM (nominal speed of the induction machine); during the starting, the torque of the machine is limited at its nominal value 51 Nm. In the instant t = 0.3s is applied a load torque equal to 40 Nm and finally is introduced a reversing in t = 0.5s, changing the speed reference from 1430 RPM to -1430 RPM (-149.7 rad/s). The torque reference generated by the speed controller is different from zero during the transients and load torque steps and can be appreciate a good tracking of the speed (Fig. 3.a and Fig. 4.a), torque (Fig. 3.b and Fig. 4.b) and stator flux (Fig. 3.c and Fig. 4.c) to their references. Fig. 3.d and Fig. 4.d indicates the behaviour of the output current where is visualized the frequency changes depending of the motor operation, but is verified that this output current presents in all the time sinusoidal waveforms. In Fig. 3.e and Fig. 3.f, results shown the chaotic behaviour of the input current and reactive power, but when the term that minimizes the reactive power is included in the cost function g, i.e. $C \neq 0$, the input current (Fig. 4.e) is in phase with its respective phase voltage except when the reversal manoeuvring is applied, as expected. In the second case, a good behaviour of the reactive power is appreciated in Fig. 4.f, because it is maintained always closes to zero.

The simulation results were done with the exact parameters of the machine, Table I. A future research is the study of the control sensibility with changes in the system parameters.

VI. Conclusions

A very simple and effective predictive torque and flux control method with reactive power minimization applied in an indirect matrix converter has been presented in this publication. The strategy offers the possibility to control both the input currents, to maintain unity power factor, and the output voltage or machine's variables at the same time. The control scheme uses a discrete model of the converter, induction machine and input filter to predict the behaviour of torque, flux and input current of the system and to obtain the best-suited converter switching state considering the torque, flux and reactive power error by the evaluation of the 24 possible combinations of the topology. The ideal minimum of the cost function is zero and represents the perfect regulation of the controlled variables, this is unity power factor and a given machine torque and flux. With this control strategy, no modulators are required and also can be considered, in a very convenient form, the discrete nature of the switching state of the converter and the function of the microprocessor used to obtain the predictions.

Appendix

The simulation parameters are detailed in Table I.

TABLE I
SIMULATION PARAMETERS

Variables	Description	Simulation
V_s	RMS supply phase voltage	540(V)
f_s	Supply frequency	50(Hz)
Input Filter		
L_f	Input filter inductance	400(μH)
C_f	Input filter capacitor	21(μF)
R_f	Input filter resistance	0.5(Ω)
Load		
P_n	Nominal power	4(kW)
I_n	Nominal current	12(A)
ω_n	Nominal speed	1430(RPM)
T_n	Nominal torque	51(Nm)
R_s	Stator resistance	1.35(Ω)
L_s	Stator inductance	0.2861(mH)
R_r	Rotor resistance	7.2037(Ω)
L_r	Rotor inductance	0.2861(mH)
L_m	Magnetization inductance	0.2822(mH)
P	Pole Number	2
Control Method -		
T_s	Sample time	10(μs)
q_s^*	Reactive power reference	0(VA)
A	weighting factor	63
B	weighting factor	14000
C	weighting factor	1

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